

Contextual Query Using Bell Tests

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Abstract

Tests are essential in Information Retrieval and Data Mining in order to evaluate the effectiveness of a query. An automatic measure tool intended to exhibit the meaning of words in context has been developed and linked with Quantum Theory, particularly entanglement. Quantum like experiments were undertaken on semantic space based on the Hyperspace Analogue Language (HAL) method. A quantum HAL model was implemented using state vectors issued from the HAL matrix and query observables, testing a wide range of window sizes. The Bell parameter S , associating measures on two words in a document, was derived showing peaks for specific window sizes. The peaks show maximum quantum violation of the Bell inequalities and are document dependent. This new correlation measure inspired by Quantum Theory could be promising for measuring query relevance.

Keywords: Bell inequality, entanglement, information retrieval, co-occurrence, HAL, tests, context, IR algorithms, Quantum Theory

1 Introduction

In this work we present original quantum-like tests that could be useful in the domain of Information Retrieval (IR) and Data Mining.

Context is used to disambiguate terms. Melucci[1] showed that a query or a document can be generalized, in different contexts, as vectors, where the likelihood of context of a set of documents can be considered. Quantum Mechanics (QM) has been invoked to enrich the search capabilities in IR by Rijsbergen[2] by using the mathematical formalism of the Hilbert vector space.

Analogies between concepts issued from Quantum Theory with Information Retrieval tools have been made by several authors. Widdows[3] uses the quantum formalism for experiences with negation and disjunction and Arafat[4] shows that user needs can be represented by a state vector. Other analogies have been stated by Li & Cunningham[5] such as: state vector/objects in a collection; observable/query, eigenvalues/relevance or not for one object; probability of getting one eigenvalue/relevance degree of object to a query. Bruza and Cole explicitly calculated eigenvectors associated to a word[6] and in the field of concept representation associated with the CHSH inequality an explicit Bell inequality violation was found[7].

2 Bell Inequality and Bell Parameters for binary outcomes

Entanglement, which can be made manifest through Bell inequality violations[8] (commonly presented in the form of the CHSH inequality[9]) has become a very important research trend in Physics. Several experiments have proved the existence of entangled particles[11, 10] and this fact is now widely accepted. This field has fascinated many scientists throughout the last decades also leading to much parallel scientific and pseudoscientific research as is well described by Keiser in a

recent book[12]. Part of the attraction arises because of the concept of nonlocality of the quantum world suggesting spooky action at distance (a discussion can be found in[13]). Even though in general the violation of Bell inequalities demands entanglement, higher violations of the inequalities do not necessarily mean mandatorily more entanglement.

Quantum Information has emerged bridging physics and information science. Though initially discovered in the context of foundations of Quantum Mechanics, the violations of Bell inequalities referred above are nowadays a key point in a wide range of branches of Quantum Information. Entanglement is at the heart of this field because it is seen as a potential resource for new applications such as coding or computing[14]. New theorems of the kind of Bell, named no-go theorems (for example the Kochen-Specker theorem[15]), have been proposed.

In practice most experiments have used polarized photons as the famous experiment in 1982 by Aspect et al.[11]. More sophisticated set-ups are constantly being proposed and discussed[16, 17] very often to rule out local hidden variable models.

Some macroscopic tests have been proposed in the form of thought experiments or combined with yes-no questions showing also Bell inequality violations, for example by Aerts[18].

The CHSH-Bell parameter S_{Bell} for tests with two binary outcomes, $+1$ or -1 , can be defined as follows:

$$S_{Bell} = |E(A, B) - E(A, C)| + |E(B, D) + E(C, D)| \quad (1)$$

where A , B , C and D are tests and $E(X, Y)$ stands for the expectation value of the outcome of mutual tests X and Y . We briefly recall some important facts about the Bell parameter. It is easily verified that S_{Bell} can never exceed 4. More specifically, Bell inequality is derived for the so called classical, local and separable situation where S_{Bell} lies between 0 and 2. In this case, for example, we could write $E(X, Y) = E(X) E(Y)$. The case $2 \leq S_{Bell} \leq 2\sqrt{2}$ can be achieved with quantum entangled states obtained experimentally with photons. Less underlined is the case where $S_{Bell} > 2\sqrt{2}$, also known as the Tsirelson's bound[16, 19]. This zone between $2\sqrt{2}$ and 4 is called the no-signaling region. The maximum value $S_{Bell} = 4$ can be attained with logical probabilistic constructions often named PR boxes[20].

3 Bell Tests in Semantic Space using HAL

Our approach presented here can be perceived as an experiment done on objects outside the domain of physics. The objects are words within texts. We study the relationships between words within a document; these relationships can be formed by creating a semantic space using the Hyperspace Analogue Language (HAL) method[21].

The HAL algorithm does not require any explicit human a-priori judgment. In this procedure a HAL lexical co-occurrence matrix is built with a “window” representing a span of words passed over the corpus being analyzed. The width of this window can be varied. Words within the window are recorded as co-occurring with strength inversely proportional to the number of other words separating them within the window.

The point of the co-occurrence matrix is that the rows effectively constitute vectors in a high-dimensional space, so that the elements of the normalized vectors are frequency counts (probabilities), and the dimensionality of the space is determined by the number of columns in the matrix (context vectors).

The HAL method has already been used as a tool for a physical analogy between semantic space and Quantum Theory, where at each word was associated a given spectrum (in analogy with spectral emission lines of atoms)[22].

Our method uses the HAL matrices for calculating quantum mechanical mean values of Query Observables and combining them in order to calculate a Bell parameter S_{query} .

We carried out our tests in a symmetric matrix obtained by the sum of the HAL matrix and its transpose (equivalent to run HAL backwards). This is due to the fact that we did not consider the order in which words appear in a text.

The tests were carried out on documents in English. The programming scheme of the algorithm implementation is represented in Figure 3 (Appendix).

4 Quantum model for Bell Tests using HAL

In this section we intend to define operators, in analogy with Quantum Theory, that will give a new possible approach to document queries. We make the following definitions.

4.1 Document vector states

Each document will have an associated vector. The vector state of the document is the normalized linear sum of all the words it contains. Each word vector state is extracted from the normalized lines of the symmetric HAL matrix. It is defined as:

$$|\phi\rangle = \frac{1}{\sqrt{\sum \langle w_j | w_k \rangle}} \sum |w_i\rangle \quad (2)$$

We will be interested in analyzing how two words are connected within a document, namely word A and word B . The two word vectors define a plane on the semantic space. We will not consider the part of the document corresponding to the orthogonal projection with the two words we are interested in. In this case only the projection of the vector state document in this plane is considered. The resulting state vector $|\psi\rangle$ from now on will be the document vector state. This vector can be written on two different orthogonal basis: $\{|w_A\rangle, |w_{A\perp}\rangle\}$ and $\{|w_B\rangle, |w_{B\perp}\rangle\}$. The orthogonal component vectors are obtained by the Gram-Schmidt orthogonalization process. The document vector state takes then the form:

$$|\psi\rangle = \alpha |w_A\rangle + \alpha_{\perp} |w_{A\perp}\rangle = \beta |w_B\rangle + \beta_{\perp} |w_{B\perp}\rangle \quad (3)$$

The coefficients α , α_{\perp} , β and β_{\perp} are obtained by projecting the original state $|\psi\rangle$ in the basis vectors and normalizing them in a way that the new $|\psi\rangle$ is normalized to the unity. For example

for α we have:

$$\alpha = \frac{\langle w_A | \phi \rangle}{\sqrt{\langle w_A | \phi \rangle^2 + \langle w_{A\perp} | \phi \rangle^2}} \quad (4)$$

4.2 Query operators

We want now to define query operators. The purpose of these operators is to quantify a query within this formalism. The query operators \hat{A} and \hat{B} are defined in a way that they attribute the value +1 to the component of the state that corresponds to the word meaning we are interested in, and 1 in the orthogonal direction. More precisely we will use operators acting as the spin Pauli matrix $\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ on their respective decomposition basis. We can associate these operators with observables because they are Hermitian. Explicitly:

$$\hat{A}|\psi\rangle = \alpha|w_A\rangle - \alpha_\perp|w_{A\perp}\rangle \quad , \quad \hat{B}|\psi\rangle = \beta|w_B\rangle - \beta_\perp|w_{B\perp}\rangle \quad (5)$$

Expectation values of operators are calculated in the same way as in quantum formalism, for example, the mean value in the context of ψ for the query about A is written as usual in quantum mechanics:

$$\langle A \rangle_\psi = \langle \psi | \hat{A} | \psi \rangle = \alpha^2 - \alpha_\perp^2 = 2\alpha^2 - 1 \quad (6)$$

From this example we see that we can obtain a score for the expected value of a search related to word A which corresponds to something reasonable as a score of a query in the document since it increases with α (the scalar product between the document state and the words state). The values range from +1 to 1, being +1 when the document vector is parallel to the query vector, and 1 when it is orthogonal. Following this line of thought other operators can be defined using, for example, the Pauli matrix $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$.

For the choice of the query operator $\hat{A}_x = \sigma_x$ this would be:

$$\hat{A}_x(\alpha|w_A\rangle + \alpha_\perp|w_{A\perp}\rangle) = \alpha_\perp|w_A\rangle + \alpha|w_{A\perp}\rangle \quad (7)$$

This operator switches the components of the vector state. This can be interpreted as a measure of different meaning in the document with respect to the original A direction. We do not consider the expectation values for the spin Pauli matrix $\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ due to the fact that here the components of the vector state issued from the HAL matrix are always real, then the expectation values associated to this operator are zero. Possible future generalizations may include a way of obtaining vector components on the complex plane.

4.3 Combining operators and expectation values of two queries

For technical reasons we choose one of the basis given above in Eq. 5 and write the operators with respect to this basis. If we choose the basis relative to A , we can write the transformation matrix M from the A basis to the B basis. It is easy to see that:

$$\hat{M} = \begin{pmatrix} \langle w_B | w_A \rangle & \langle w_B | w_{A\perp} \rangle \\ \langle w_{B\perp} | w_A \rangle & \langle w_{B\perp} | w_{A\perp} \rangle \end{pmatrix} \quad (8)$$

By construction, this matrix can be simply expressed by the parameter $p = \langle w_B | w_A \rangle$ which is always positive and smaller than 1, unless there is a perfect alignment between the two words. The matrix can thus be written as

$$\hat{M} = \begin{pmatrix} p & \sqrt{1-p^2} \\ \sqrt{1-p^2} & -p \end{pmatrix} \quad (9)$$

Any operator expressed in its matrix form on the basis associated to B can be written in the basis associated to A using the transformation matrix M . From our previous definition of \hat{B} , its matrix form in the basis associated to A becomes:

$$\hat{B} = \begin{pmatrix} 2p^2 - 1 & 2p\sqrt{1-p^2} \\ 2p\sqrt{1-p^2} & 1 - 2p^2 \end{pmatrix} \quad (10)$$

With the two operators written in a common basis we can now combine two query operators and easily calculate mean values. For example we get:

$$\langle \hat{A}\hat{B} \rangle_\psi = 2p^2 - 1 \quad (11)$$

The expected value of a joint query is then uniquely determined by the inner product of the two word states. Note that even though $\hat{A}\hat{B} \neq \hat{B}\hat{A}$, meaning that the observables \hat{A} and \hat{B} do not commute, we have the equality when we take the mean values $\langle \hat{A}\hat{B} \rangle_\psi = \langle \hat{B}\hat{A} \rangle_\psi$.

4.4 Bell parameter calculation

Bell tests are usually a proof of a non-separability of the combination of two different systems. This case is not completely analogous. In fact we are dealing with only a two dimensional space which can be understood as the sense associated to a word A in a document or the sense of another word B . For purposes of document analysis we have chosen to take an approach leading to the calculation of a Bell parameter as defined in Eq. 1. Concretely we calculate quantum mean values with different query operators which can be considered as measuring devices:

$$S_{query} = \left| \langle \hat{A}\hat{B}_+ \rangle + \langle \hat{A}_x\hat{B}_+ \rangle \right| + \left| \langle \hat{A}\hat{B}_- \rangle - \langle \hat{A}_x\hat{B}_- \rangle \right| \quad (12)$$

using the following operators

$$\hat{A}; \hat{A}_x; \hat{B}_+ = -\frac{B + \hat{B}_x}{\sqrt{2}}; \hat{B}_+ = \frac{B - \hat{B}_x}{\sqrt{2}} \quad (13)$$

Our particular operator choice was inspired from the usual example that maximizes the violation of the Bell inequalities for a particular Bell state of two qubits[14], even though our global model is different. All operators have the property of being their own inverse, that is, their square is the identity (property of the Pauli matrices) which means that their eigenvalues are $+1$ and -1 . With this we can calculate the corresponding parameters considering different queries among different documents. Two examples are presented in the next section.

5 Results and Discussion

With the formalism established we are in a position to apply it to different documents. We calculated the Bell parameter defined in Eq. 12 and we will discuss the results in a relevance perspective. In the following examples all the documents are taken from Wikipedia.

5.1 Test on Documents: Reagan and Iran

As a first application we considered an example originally introduced by Bruza and Cole[6], which is the query for the word Reagan in the context of Iran. If we talk about Reagan alone one usually associates this with the fact that he was President, but if we include Iran it will be more likely that we are interested in the Iran-contra scandal. Four documents were considered which are close to the query: Reagan administration scandals¹, Reagan², IranContra affair³ and Iran⁴.

We plot the parameters S_{query} defined above in Eq. 12 as a function of the HAL window for the query of the words Reagan and Iran. The results are shown in Figure 1.

There is clearly a common behavior for the three queries in the documents (with just one exception): the parameter starts from zero and increases until it reaches a maximum, never crossing the Tsirelson's bound $2\sqrt{2}$, but getting very close to it, and then drops again. This suggests that each document, given a two word query, has an optimal HAL window size that maximizes the parameter S_{query} . For the query of Iran - Reagan, among the four documents, it is predictable that the document that is more closely related to this query is the Iran-Contra affair, followed by the documents: Reagan administration scandals and Reagan, with an expected greater relevance for the first.. The least related document should be Iran. At first sight it may appear that since we are looking for Reagan - Iran, the documents Reagan and Iran should appear on the same level in the search.. However in general, the meaning Reagan has less importance in the context Iran (because the common concept Iran includes its history, culture, geographical situation, etc.) than Iran in the context of Reagan. In Figure 1 we also observe that this is basically the order in which the peaks

¹http://en.wikipedia.org/wiki/Reagan_administration_scandals (accessed 12/04/2013)

²<http://en.wikipedia.org/wiki/Reagan> (accessed 12/04/2013)

³http://en.wikipedia.org/wiki/Iran-Contra_affair (accessed 12/04/2013)

⁴<http://en.wikipedia.org/wiki/Iran> (accessed 12/04/2013)

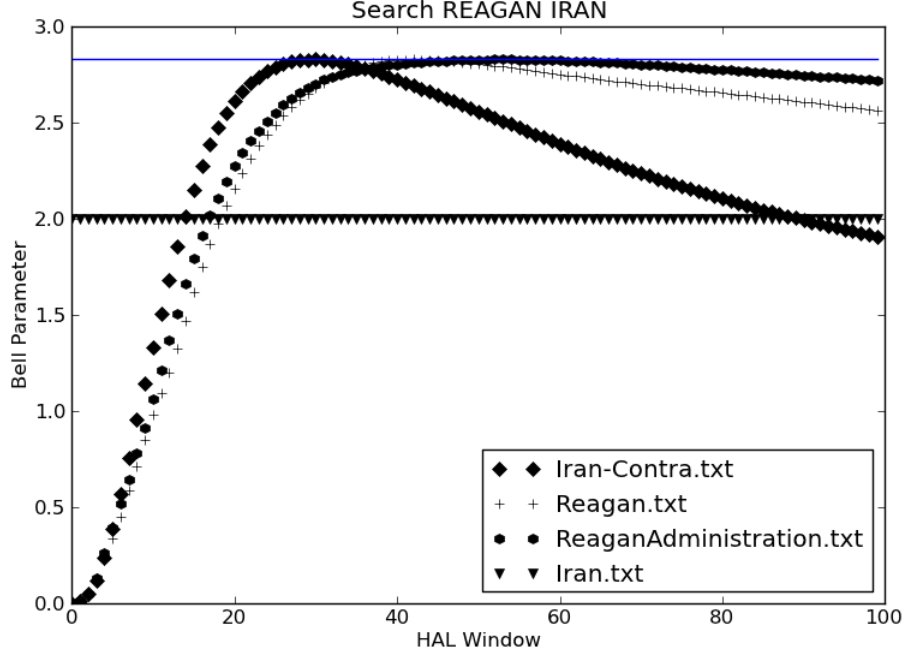


Figure 1: Bell parameter for the query of words Reagan - Iran in four documents: Reagan administration scandals, Reagan, Iran-Contra affair and Iran

appear.

The document regarding Iran always gives a constant value of 2. This fact is easily explained in the framework of our model. In fact it is not hard to see that when we do a two word query in which one of them is not present in the document, the result for S_{query} is always 2. Besides if neither of the two words is present the result is always zero. Let us now consider the other three documents.

The first peak appears using a window length around $l = 30$. The S_{query} curve peaks before this value in the document of Iran-Contra affair. The other two documents cannot be clearly distinguished. This corresponds to our previous prediction. In fact, it makes sense that the sooner a peak appears the less interaction, in the sense of window length, we have to consider in order to obtain high correlation between words. Bearing this in mind, the document Iran-Contra affair is clearly the one selected by the model. The other two documents (Reagan and Reagan administration scandals) are not clearly distinguishable. On one side the peak of the Reagan document appears first, but the curve for Reagan administration scandals has a bigger extension close to the Tsirelson's bound $2\sqrt{2}$, meaning high correlation for several window sizes, which can also be a clue for some strong correlation between words.

5.2 Test on Documents about Orange

The second case considered concerns the polysemy of the word orange and associated concepts. In this example we are interested in the ambiguity between the meanings color and fruit. We also

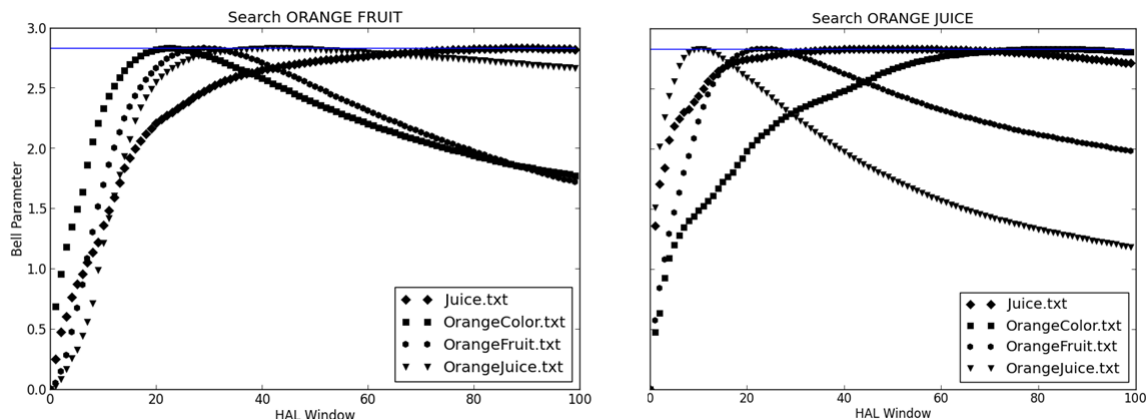


Figure 2: Bell parameter for the query on the words Orange - Fruit and Orange - Juice in four different documents: Juice, Orange (Color), Orange (Fruit) and Orange Juice.

associate the concept of juice. The documents considered were: Orange (Colour)⁵, Orange (Fruit)⁶, Orange Juice⁷ and Juice⁸. Two queries are considered: Orange Fruit and Orange Juice. The results are presented in Figure 2.

The query Orange - Fruit presents the first peak around $l = 22$ for the document Orange color, the second in $l = 29$ for the document Orange fruit, then for $l = 40$ the document Orange juice and very far away the document Juice. It is interesting to note that, even though the peaks are close, the peak of the curve Orange - Color appears before the one for Orange - Fruit. This may be the suggestion of a strong correlation between the origin of the name of the color and the name of the fruit. The poor correlation of the general term Juice with the specific query Orange - Fruit is very clear on the graph according to this criterion.

Finally, the last query was Orange - Juice. Again, here, we recover precisely the order that we would expect for the documents: Orange juice, Orange Fruit, Juice and Orange Color. It is worth noticing that in the latter case the peak corresponds to a window length range considered to be optimal for implementation of HAL ($l = 10$) which may indicate an even a stronger correlation between the words.

6 Conclusion and Perspectives

In this work, we presented a novel search experiment based on the Bell parameter extraction in semantic space using the HAL method.

The semantic vectors in HAL are representations that are essentially measures of context. The HAL method has already been used for the analogies with Quantum Theory by Bruza[23] for activating associations of concepts and by Wittek and Darny[22] for extracting spectral content

⁵[http://en.wikipedia.org/wiki/Orange_\(colour\)](http://en.wikipedia.org/wiki/Orange_(colour)) (accessed 12/04/2013)

⁶[http://en.wikipedia.org/wiki/Orange_\(fruit\)](http://en.wikipedia.org/wiki/Orange_(fruit)) (accessed 12/04/2013)

⁷http://en.wikipedia.org/wiki/Orange_juice (accessed 12/04/2013)

⁸<http://en.wikipedia.org/wiki/Juice> (accessed 12/04/2013)

from the semantic space. HAL shows high potentiality because it is a simple way to build a semantic space with a measure that is independent of user judgment.

The main feature of Quantum Theory explored in this work is the violation of the Bell inequalities which can be related to entanglement and non-locality, impossible at a classical level. The results show Bell inequality violation up to the maximal value of $S_{Bell} = 2\sqrt{2}$, (the Tsirelsons bound). In our model each document is associated to a two dimensional Hilbert space (dependent on the search we are interested in), and queries are observables acting on it. A Bell parameter is then defined. We found that the Bell parameter is strongly dependent on the HAL window size. From our results it is suggested that for this kind of model there is an optimal window size that maximizes the Bell parameter. This is reminiscent of what was also noticed by Bruza and Woods[23]: if the window size is set too large spurious co-occurrence associations are represented in the matrix and, if the window size is too small, relevant associations may be missed. In this model we see that too large windows may also dilute connections between associated words.

Only one document, the one that did not present one of the words of the query, did not violate the Bell inequality. In general, a pattern of early appearance of the peak (smallest window sizes) seems to be related to the relevance of the document for the search. In a near future other measures of quantum properties (as proper measures of entanglement) will also serve to make a better comparison between the results issued from the standard information retrieval methods. It is not clear how to interpret the Bell inequality violation here and what is the meaning of the optimal length that maximizes the Bell parameter.

Can correlation and entanglement give a measure of query relevance? Experiments and systematic comparisons with other methods used in IR, such as Latent Semantic Analysis (LSA) and the ranking method Okapi BM25, could give further indications. An important technical point is that we introduced a new tool which has connections with the Quantum Theory: query observables. Here we made a practical choice similar to the spin Pauli matrices, but we think that it should be possible, after much experimentation on different documents, to introduce new families of query observables adapted to different purposes and contexts. In the domain of IR many concepts are introduced to define, for example, opinion-like queries in social networks[24]. Efforts are also being made in order to diversify query results of ambiguous queries considering concepts such as sentiment diversification to identify positive, negative and neutral sentiments about the search topic considered[25].

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Appendix: Bell test HAL algorithm

The algorithm was implemented using Python programming language along with the string module and pylab. All words are considered and simple plurals (constructed by adding an s) are

treated as if singular words. Lower and upper case letters are not distinguished, which means that if two words differ from each other by changes on the case, they are considered equivalent. Even if words have the same origin, they are treated differently (for example battle and battling are distinct).

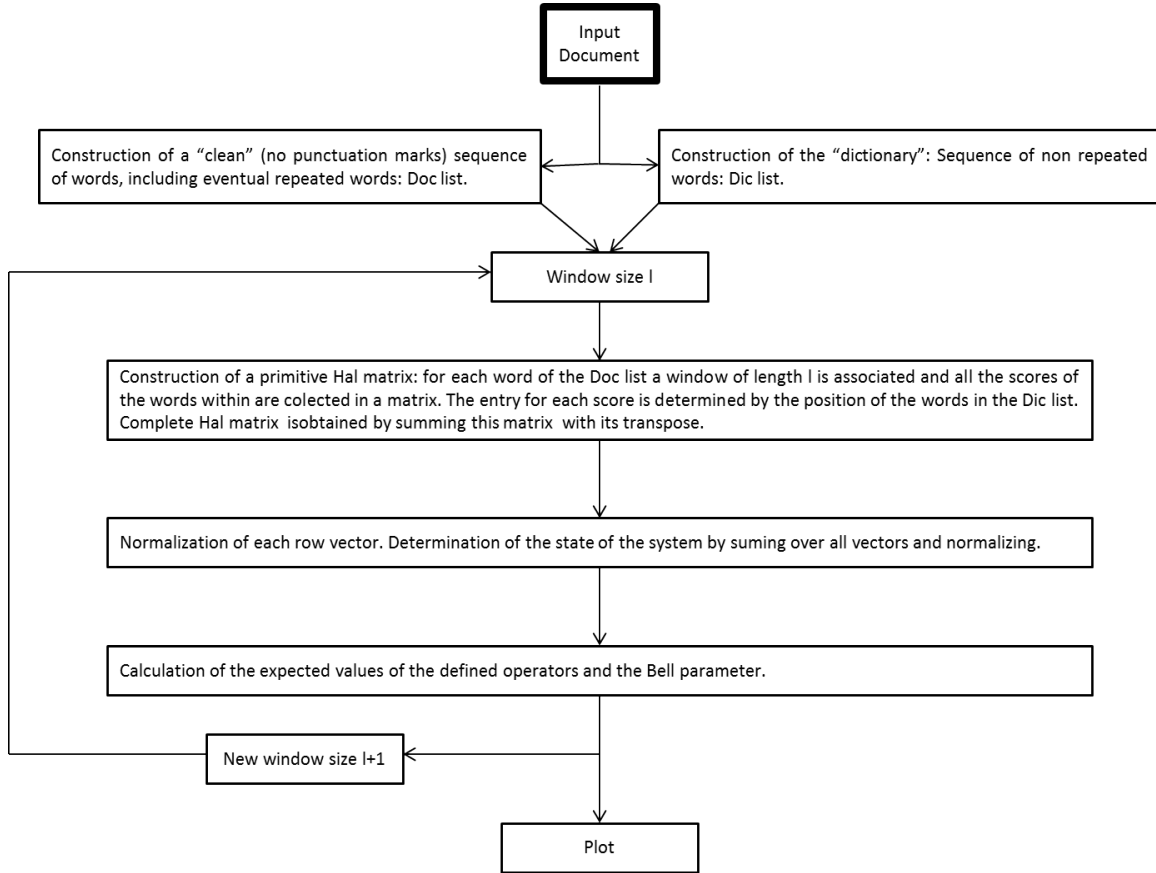


Figure 3: Flow diagram of the Quantum HAL algorithm described.

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